Advances in Causal Inference Workshop, UAI 2015
July 16, 2015

MAX-PLANCK-GESELLSCHAFT

Causal interpretation rules for encoding and decoding models in neuroimaging

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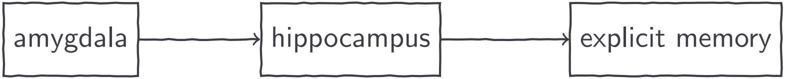
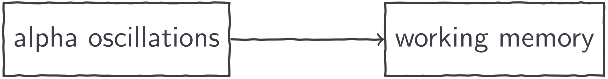
sweichwald.de/neuroimage2015 🌍 brain-computer-interfaces.net

Motivation



Hippocampal activity in this study was correlated with amygdala activity, supporting the view that the amygdala **enhances** *explicit memory by* **modulating** *activity in the hippocampus.*

(S. Hamann, *Trends in Cognitive Sciences*, 2001)



We tested [...] whether pre-stimulus alpha oscillations measured with electroencephalography (EEG) **influence** *the encoding of items into working memory.*

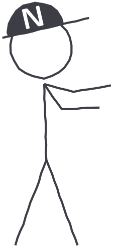
(Myers et al., *Journal of Neuroscience*, 2014)

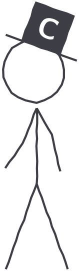
Overview

1. Motivation
2. Approach
3. Encoding and decoding models in neuroimaging
4. Causal interpretation of encoding and decoding models
5. Empirical example
6. Wrap-up

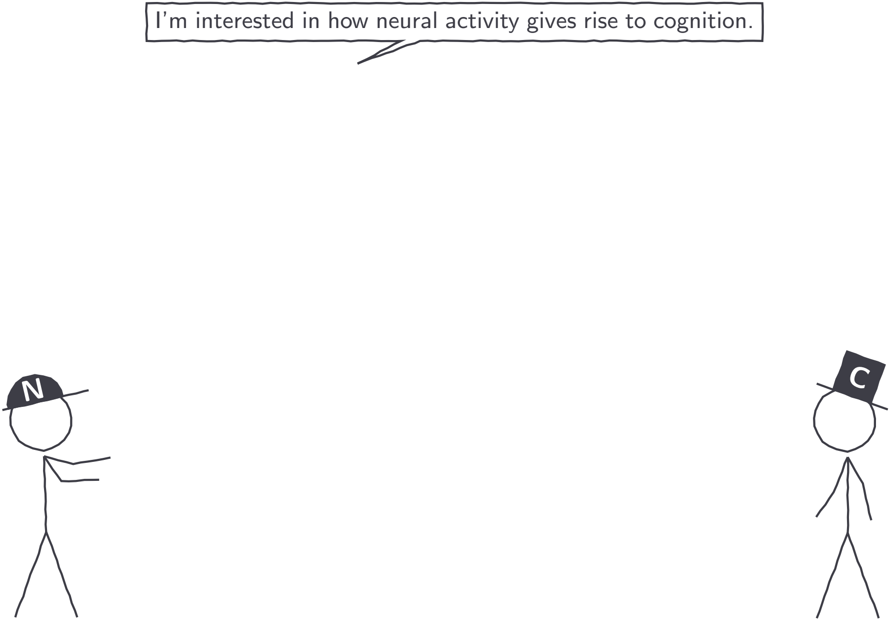
Approach

Neuroimaging analysis methods in a causal framework

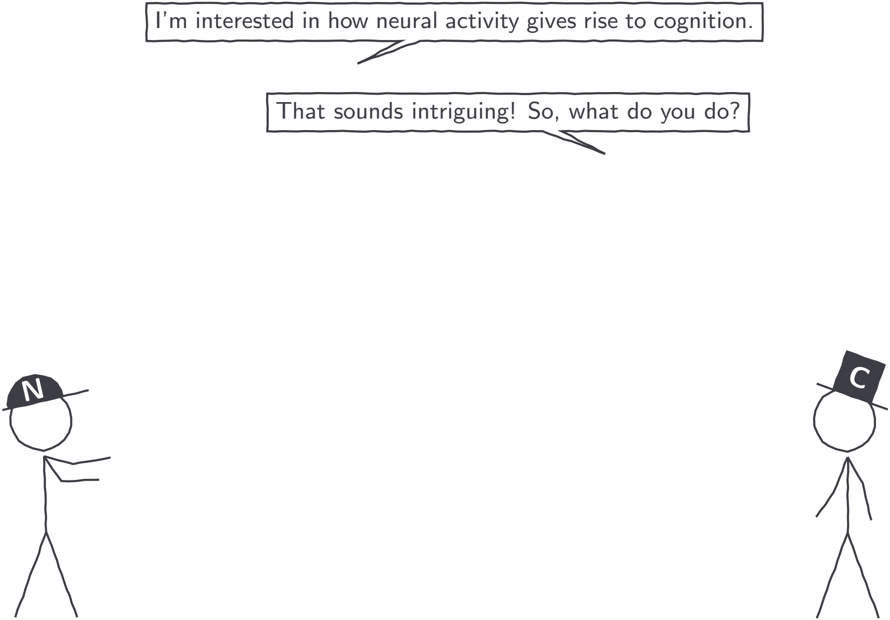




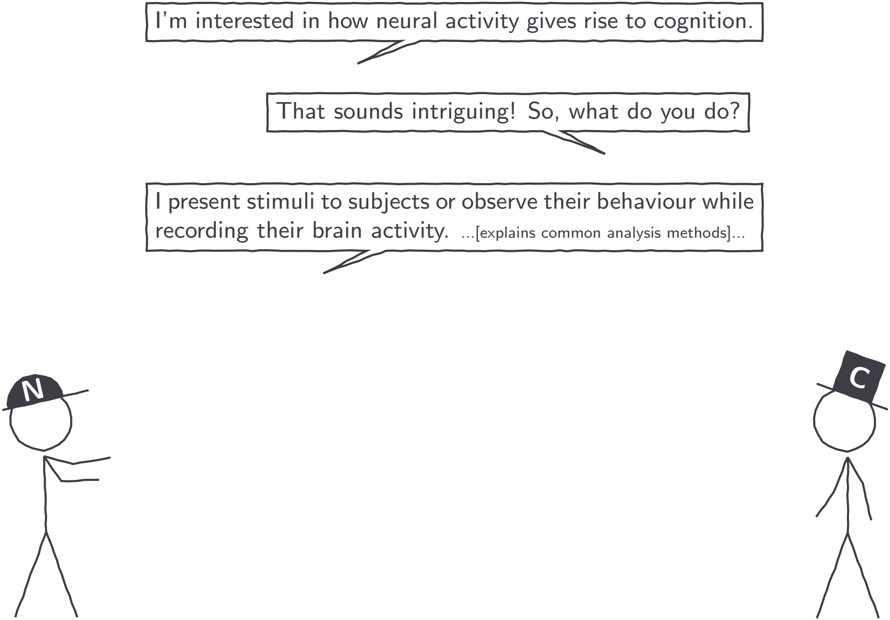
Neuroimaging analysis methods in a causal framework


I'm interested in how neural activity gives rise to cognition.
N
C

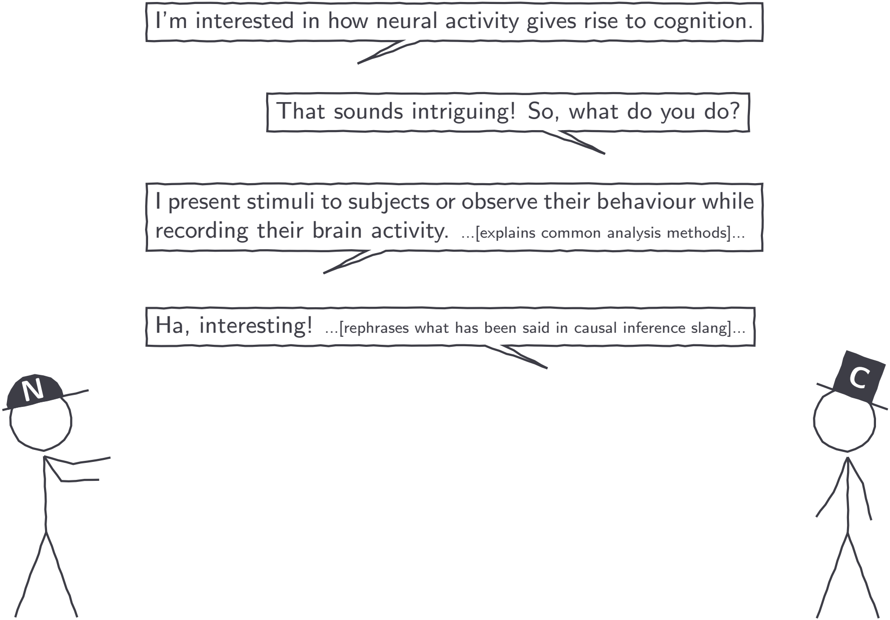
Neuroimaging analysis methods in a causal framework


I'm interested in how neural activity gives rise to cognition.
That sounds intriguing! So, what do you do?
N
C

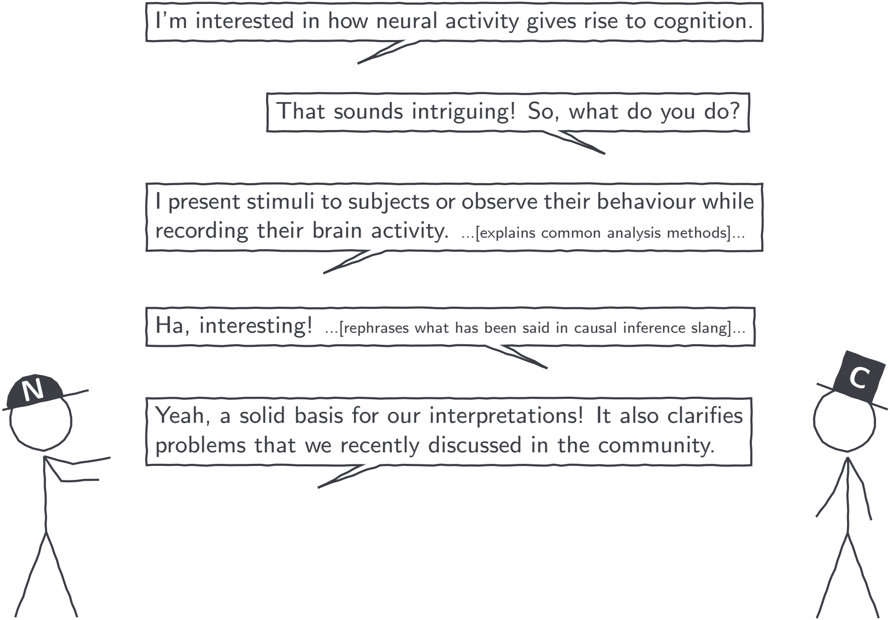
Neuroimaging analysis methods in a causal framework


I'm interested in how neural activity gives rise to cognition.
That sounds intriguing! So, what do you do?
I present stimuli to subjects or observe their behaviour while recording their brain activity. ...[explains common analysis methods]...
N
C

Neuroimaging analysis methods in a causal framework

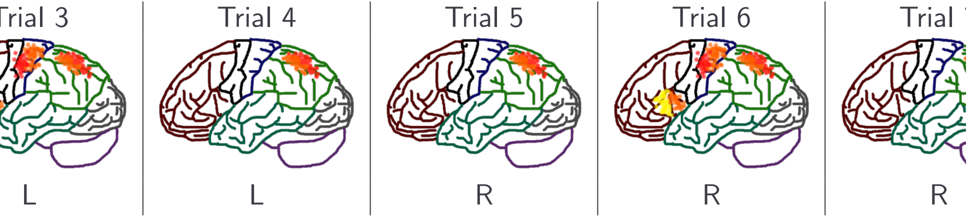

I'm interested in how neural activity gives rise to cognition.
That sounds intriguing! So, what do you do?
I present stimuli to subjects or observe their behaviour while recording their brain activity. ...[explains common analysis methods]...
Ha, interesting! ...[rephrases what has been said in causal inference slang]...
N
C

Neuroimaging analysis methods in a causal framework


I'm interested in how neural activity gives rise to cognition.
That sounds intriguing! So, what do you do?
I present stimuli to subjects or observe their behaviour while recording their brain activity. ...[explains common analysis methods]...
Ha, interesting! ...[rephrases what has been said in causal inference slang]...
Yeah, a solid basis for our interpretations! It also clarifies problems that we recently discussed in the community.
N
C

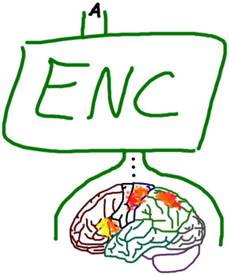
Encoding and decoding models in neuroimaging

Neuroimaging data



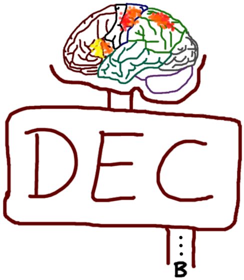
Encoding and decoding models

encoding



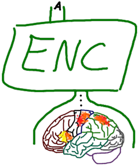
e.g. mean difference
between conditions

decoding



e.g. classifier for
experimental conditions

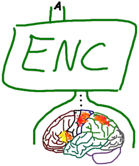
Relevance in encoding and decoding



“Feature shows significant variation across experimental conditions?”

“Feature helpful for predicting the experimental condition?”

Relevance in encoding and decoding



“Feature shows significant variation across experimental conditions?”

“Feature helpful for predicting the experimental condition?”

relevant feature $\overset{?}{\leftrightsquigarrow}$ cognitive process

Causal interpretation of encoding and decoding models

Towards a causal framework

Let’s set out the causal component of already performed analyses..

Towards a causal framework

Let's set out the causal component of already performed analyses..

stimulus- vs response-based

feature relevance $\not\leftrightsquigarrow$ marginal/conditional dependence

$\rightsquigarrow$ 16 causal interpretation rules

Towards a causal framework

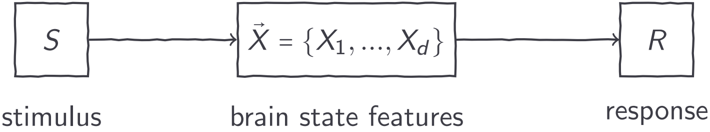
Let's set out the causal component of already performed analyses..

stimulus- vs response-based

feature relevance $\leftrightsquigarrow$ marginal/conditional dependence

$\rightsquigarrow$ 16 $\underbrace{\quad}_{\text{simple}}$ causal interpretation rules

Stimulus- vs response-based



S

stimulus

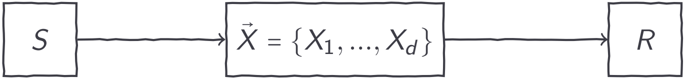
$\vec{X} = \{X_1, ..., X_d\}$

brain state features

R

response

Stimulus- vs response-based



$$S \longrightarrow \vec{X} = \{X_1, \ldots, X_d\} \longrightarrow R$$

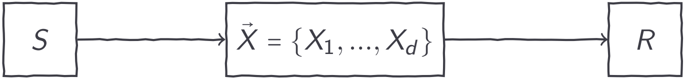
stimulus

brain state features

response

stimulus-based		response-based
$p(\vec{X}\|S)$	encoding	$p(\vec{X}\|R)$
$p(S\|\vec{X})$	decoding	$p(R\|\vec{X})$

Stimulus- vs response-based



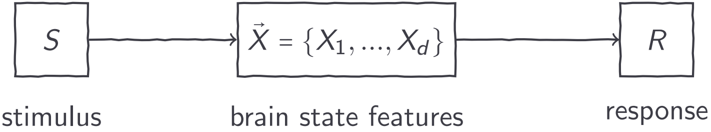
stimulus

brain state features

response

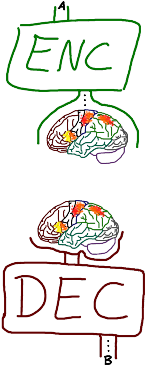
	stimulus-based		response-based	
$p(\vec{X}\|S)$	causal	encoding		$p(\vec{X}\|R)$
$p(S\|\vec{X})$		decoding	causal	$p(R\|\vec{X})$

Stimulus- vs response-based

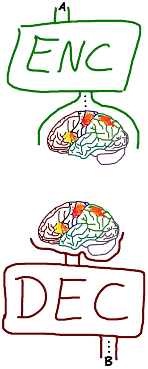


	stimulus-based		response-based	
$p(\vec{X}\|S)$	causal	encoding	*anti*-causal	$p(\vec{X}\|R)$
$p(S\|\vec{X})$	*anti*-causal	decoding	causal	$p(R\|\vec{X})$

Relevance and dependence

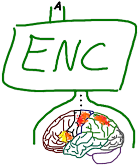


Relevance and dependence



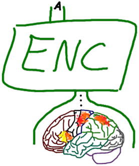
$$p(X_i|C = c_1) \overset{?}{\neq} p(X_i|C = c_2)$$

Relevance and dependence



$$p(X_i|C = c_1) \overset{?}{\neq} p(X_i|C = c_2) \qquad X_i \not\perp C$$

Relevance and dependence

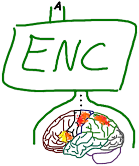


$$p(X_i|C = c_1) \overset{?}{\neq} p(X_i|C = c_2)$$

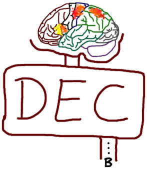
$$X_i \not\perp C$$

$$p(C|\vec{X}) \overset{?}{\neq} p(C|\vec{X} \setminus X_i)$$

Relevance and dependence



$$p(X_i|C = c_1) \overset{?}{\neq} p(X_i|C = c_2) \qquad X_i \not\perp C$$



$$p(C|\vec{X}) \overset{?}{\neq} p(C|\vec{X} \setminus X_i) \qquad X_i \not\perp C|\vec{X} \setminus X_i$$

Causal interpretation rules (1)

Causal interpretation rules (1)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	×		
	√		
		×	
		√	
Response-based	×		
	√		
		×	
		√	

Causal interpretation rules (1)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	×		
	✓		
		×	
		✓	
Response-based	×		
	✓		
		×	
		✓	

$$X_i \not\perp R$$

$$X_i \leftarrow h \rightarrow R$$

$$X_i \rightarrow R$$

Causal interpretation rules (1)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	×		
	√		
		×	
		√	
Response-based	×		
	√		
		×	
		√	

Causal interpretation rules (1)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	×		
	√		
		×	
		√	
Response-based	×		
	√		inconclusive
		×	
		√	

Causal interpretation rules (1)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	×		
	√		
		×	inconclusive
		√	inconclusive
Response-based	×		
	√		inconclusive
		×	inconclusive
		√	inconclusive

Causal interpretation rules (1)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	×		no effect of S
	√		effect of S
		×	inconclusive
		√	inconclusive
Response-based	×		no cause of R
	√		inconclusive
		×	inconclusive
		√	inconclusive

Causal interpretation rules (2)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	√	√	
	√	×	
	×	√	
	×	×	
Response-based	√	√	
	√	×	
	×	√	
	×	×	

Causal interpretation rules (2)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	√	√	🟩
	√	×	
	×	√	
	×	×	
Response-based	√	√	inconclusive
	√	×	🟩
	×	√	
	×	×	

Causal interpretation rules (2)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	✓	✓	
	✓	×	
	×	✓	
	×	×	
Response-based	✓	✓	inconclusive
	✓	×	
	×	✓	
	×	×	

$X_i \not\perp\!\!\!\perp S$ and $X_i \perp\!\!\!\perp S | \vec{X} \setminus X_i$

$S \dashrightarrow X_i$ indirectly

Causal interpretation rules (2)

	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	√	√	🟩
	√	×	
	×	√	
	×	×	
Response-based	√	√	inconclusive
	√	×	🟩
	×	√	
	×	×	

Causal interpretation rules (2)

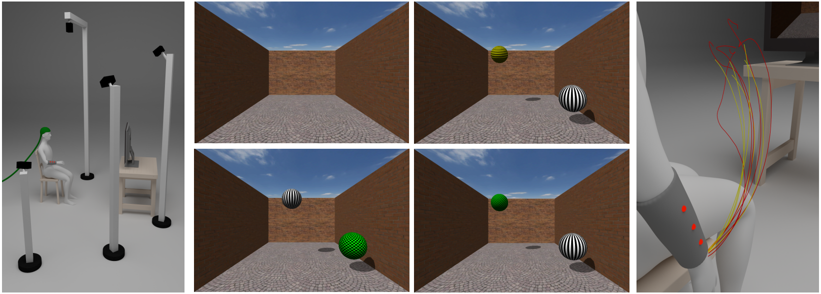
	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	✓	✓	indirect effect of S
	✓	×	
	×	✓	
	×	×	
Response-based	✓	✓	inconclusive
	✓	×	
	×	✓	
	×	×	

Causal interpretation rules (2)

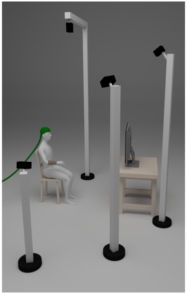
	Feature X_i relevant?		
	Encoding	Decoding	Causal interpretation
Stimulus-based	√	√	effect of S
	√	×	indirect effect of S
	×	√	provides context
	×	×	no effect of S
Response-based	√	√	inconclusive
	√	×	no direct cause of R
	×	√	provides context
	×	×	no cause of R

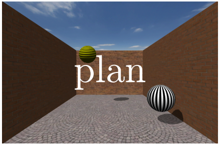
Empirical example

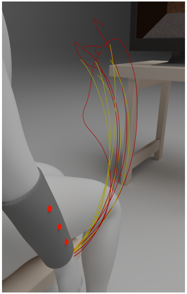
Visuo-motor learning task



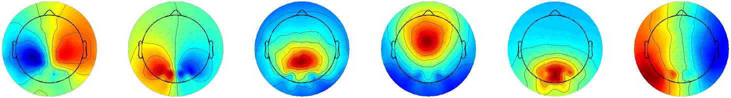
Visuo-motor learning task



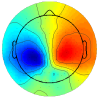
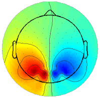
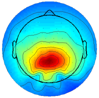
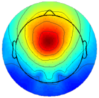
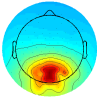
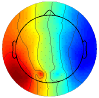




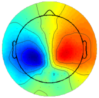
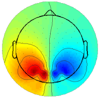
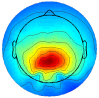
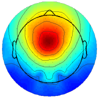
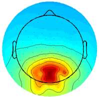
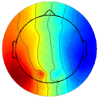
(Relevant) Features



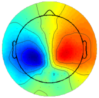
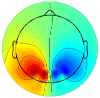
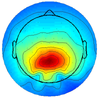
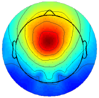
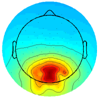
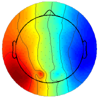
(Relevant) Features

	α_{IC_1}	α_{IC_2}	α_{IC_3}	α_{IC_4}	α_{IC_5}	α_{IC_6}
						

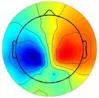
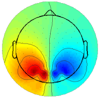
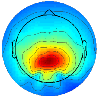
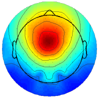
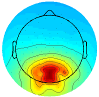
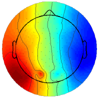
(Relevant) Features

p-values	α_{IC_1} 	α_{IC_2} 	α_{IC_3} 	α_{IC_4} 	α_{IC_5} 	α_{IC_6} 
Encoding						
Decoding						

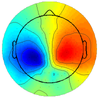
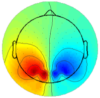
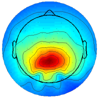
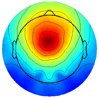
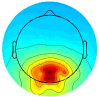
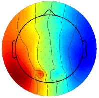
(Relevant) Features

p-values	α_{IC_1} 	α_{IC_2} 	α_{IC_3} 	α_{IC_4} 	α_{IC_5} 	α_{IC_6} 
Encoding	0	0	0	0	0	0
Decoding	0	0	0.50	0.34	0.79	0.13

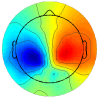
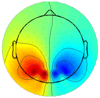
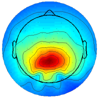
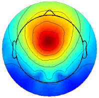
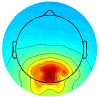
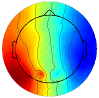
(Relevant) Features

p-values	α_{IC_1} 	α_{IC_2} 	α_{IC_3} 	α_{IC_4} 	α_{IC_5} 	α_{IC_6} 
Encoding	0	0	0	0	0	0
Decoding	0	0	0.50	0.34	0.79	0.13

Causal analysis

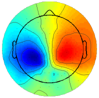
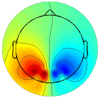
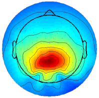
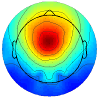
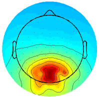
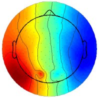
p-values	α_{IC_1} 	α_{IC_2} 	α_{IC_3} 	α_{IC_4} 	α_{IC_5} 	α_{IC_6} 
Encoding	0	0	0	0	0	0
Decoding	0	0	0.50	0.34	0.79	0.13

Causal analysis

p-values	α_{IC_1} 	α_{IC_2} 	α_{IC_3} 	α_{IC_4} 	α_{IC_5} 	α_{IC_6} 
Encoding	0	0	0	0	0	0
Decoding	0	0	0.50	0.34	0.79	0.13

- instruction to plan a reaching movement is causal for all α_{IC_i}
- $\alpha_{\text{IC}_3}, \ldots, \alpha_{\text{IC}_6}$ are only indirect effects

Causal analysis

p-values	α_{IC_1} 	α_{IC_2} 	α_{IC_3} 	α_{IC_4} 	α_{IC_5} 	α_{IC_6} 
Encoding	0	0	0	0	0	0
Decoding	0	0	0.50	0.34	0.79	0.13

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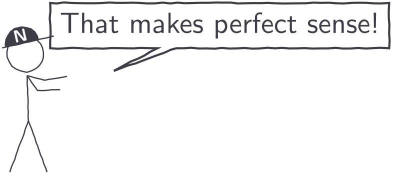

Wrap-up

N

C

feature relevance

feature relevance ↭ (conditional) (in)dependence

feature relevance $\leftrightsquigarrow$ (conditional) (in)dependence $\leftrightsquigarrow$ causal structure

feature relevance ↭ (conditional) (in)dependence ↭ causal structure

- simple interpretation rules
- reinterpretation of previous results?
- resolve recently discussed issues

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- simple interpretation rules
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Sebastian Weichwald, Timm Meyer, Ozan Özdenizci, Bernhard Schölkopf, Tonio Ball, Moritz Grosse-Wentrup:

- Causal interpretation rules for encoding and decoding models in neuroimaging. *NeuroImage*, 2015.
- Causal and anti-causal learning in pattern recognition for neuroimaging. *PRNI*, 2014.